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JOINTS IN FIBER-REINFORCED ALUMINUM ALLOYS

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16. Abstract

The problems of the joints in boron-fiber-reinforced aluminum alloys is discussed using diffusion-welded connecting elements for which static and dynamic strength was determined.

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Abstract

The problems of the joints in boron-fiber-reinforced aluminum alloys is discussed using diffusion-welded connecting elements for which static and dynamic strength was determined.

One of the major, and still not completely solved problems in design with metallic fiber materials is the development and control of suitable joining methods and the shaping of the connection point. Just because the fiber material is shapable only within definite limits, construction means that do not require machining or plastic deformation of the material are preferred.

The currently common structural elements under the name of mixed construction use the fiber material only for the purpose of stiffening or reinforcing certain parts. Movable or separable connections are preferably made of commercially available isotropic materials because of the complex stresses which appear in those parts, while elements with tensile or compressive stress in only one or two axes can be design in fiber technology with a great saving in weight.

Force transfer between the fiber composite element and the connecting part, or between two elements of fiber material, must receive special attention in design. The form of the connection must be designed not only to meet strength and stiffness requirements, but it must also

*Numbers in margin indicate foreign pagination.

consider the structure technique used. Another important /360 viewpoint in light construction is minimizing the weight of such a connection.

Curves of normal and thrust stress are plotted in Figure 1 for two typical connecting elements. These stress curves, which are plotted only qualitatively, are important for understanding the types of fracture that occur.

In the case shown, both connections are exposed to pure tensile load produced by the force P. In section A/A of the simple overlapped connection in the upper part of the figure, the mean tensile stress rises from 0 at the end of the plate up to the stress at $x = l_o$ * which corresponds to the load B. A constant bending stress is also superimposed for this tensile stress, due to the mutual displacement of the plates. Because of the step at the beginning and end of the overlap, the tensile stress is not distributed evenly over the cross section of the plate. Rather, there is an elevated stress at the transitions. This stress increase depends, among other things, on the length of the overlap and the shape of the transition. With brittle fiber materials, this step effect is particularly serious. The shear stress in Section B/B has maxima at the boundaries of the overlap. These thrust stresses must be taken up by the bonding area between the plates. The magnitude of the stress increase is determined, on one hand, by the shape of the plate end: shaping of the plate end will reduce the peak thrust stress. Increasing the length of the overlap acts in the same sense. On the other hand, the flow and

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* Translator's note: subscript is the letter o (for 'overlap'), not a zero.

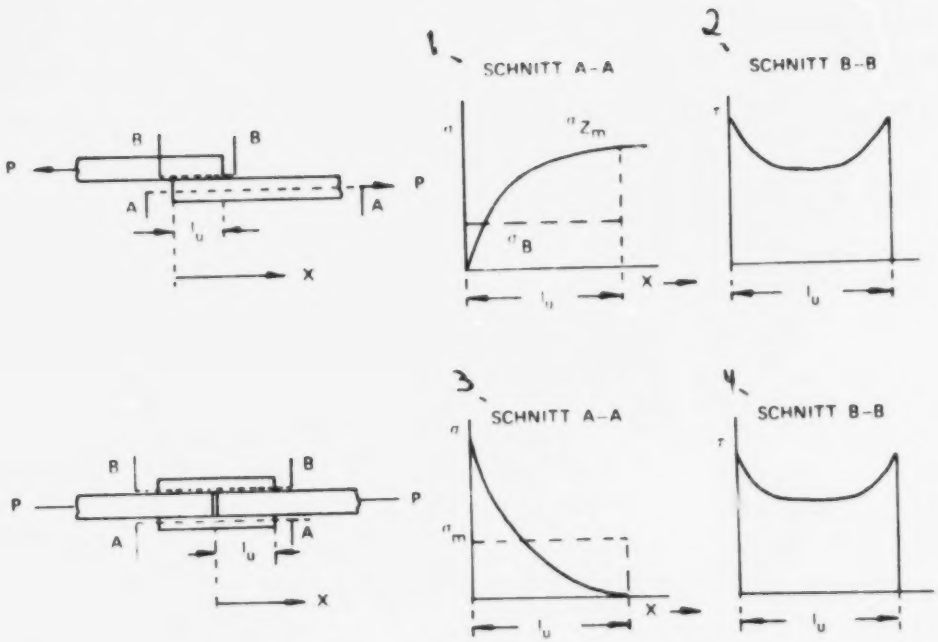

Figure 1. Qualitative stress curve for overlapped bonds.

1. Section 2. Section 3. Section 4. Section

deformation capacity of the bond enters significantly into reduction of the stress peaks by redistributing them into adjacent regions.

The lower part of the picture shows an overlap shape free of bending moment because of the symmetric arrangement of the bonding plates. The previous statements about the curve of thrust stress for the one-sided bond apply here if the overlapping plates are exposed to the same stress as the middle plate.

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In the tensile stress curve for the bonding plates the gap in the middle plate acts like a step. This stress increase can, for instance, be reduced by increasing the cross-sectional area of the bonding plates. Of course, thicker plates, due to greater stiffness, produce an greater elevation of the thrust stress.

Minimum weight is an important requirement in selection of the connection. Figure 2 shows the relation between the increased weight of a connection versus that of the undivided material and various design forms of plate bonds.

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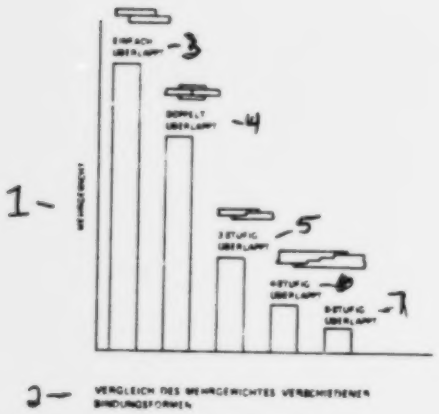

Figure 2. Weight comparison of different bonding forms.

1. Increased weight
2. Comparison of the increased weight of various bond forms
3. Singly overlapped
4. Doubly overlapped
5. 2-step overlap
6. 4-step overlap
7. 8-step overlap

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The relations are calculated for equally loadable glued connections, but apply to the same extent for all surface bonding techniques, such as soldering or diffusion welding, for instance. In this comparison, to be sure, it is assumed that the bond itself fails in the structure.

From the figure it can be seen that the multiply overlapped bond allows higher specific loading because of the more even load distribution.

Before considering particularly the structures of diffusion-welded boron-fiber-reinforced aluminum, we shall give a general survey of other processes described in the literature for force-locking bonding of fiber composite materials with an aluminum matrix.

The most important methods are summarized in the table in Figure 3.

Only low thrust strength values are attained by gluing, in comparison with metallic bonds (maximally 4.5 kp/mm² shear strength at room temperature). With temperature stresses above 100 to 150°C, heat-resistant glues are already required. Polyimides allow temperatures up to about 300°C. Then, to be sure, the shear strength decreases from 2 kp/mm² at room temperature to 1 kp/mm² at 300°C.

Soft-soldered connections exhibit clearly higher strengths at room temperature than polyimides, and at the same time have considerably higher tenacity.

Hard-soldered and diffusion-welded bonds allow considerably higher shear stresses. Boron-aluminum laminates can be soldered using an AlSi solder with shear strengths up to 12 kp/mm². With diffusion welding it is possible to achieve shear strengths comparable to that for the metallic matrix.

Figure 3. /364

JOINING METHODS FOR BORON-ALUMINUM COMPOSITE MATERIALS

Joining Method	Static shear strength in kp/mm²	Temp. in °C	Source
Gluing			
Epoxy-	up to 4.5	20	Hersh [1]
Phenolic-			
Methacrylate-resin			
Polyimide resin	2.0	20	MBB-RF-(*)
	1.0	300	Inform.
Soft solder			
Eutectic 509	7.5	20	Convair [2]
	6.1	150	Aerosp. Div.
Allstate 105	8.2	20	
	2.9	260	
Hard solder			
AlSi7	12.0	20	Kreider,
AlSi7	4 - 5	300	Breinan [3]
AlSi12	10.5		
Diffusion welding			
AlMgSi1	12 - 14	20	Olster et al. [4]
	6	300	Carlson [5] Joseph et al. [6]
Resistance welding			
Spot welding			Hersh,
Rolled seam welding			Weisinger [7]
AlMgSi	up to 14 •		

• Applies only at the welded point itself.

Resistance welding in the form of spot or rolled /365
seam welding pre-supposes about the same heat conductivity for the two materials to be joined for successful application. Then weld factors up to 100% can be achieved with this method without damaging the boron fibers.

Commercial fusion welding processes, on the other hand, generally cause severe damage to the boron fibers, resulting in inadequate strength. Mechanical connecting elements such as rivets and screws can be used successfully only if the force is introduced predominantly by frictional forces.

On a survey of the literature it appeared that there were no values for fatigue behavior of bonds of boron-aluminum laminates, but only data from static tests.

This work is intended to make possible evaluation of this jointing technology on the basis of static and dynamic stress tests on diffusion-welded bonding elements. It must be mentioned that this work was kindly supported financially by the Federal Ministry for Defense.

The samples were welded in a 20 ton vacuum hot press from the Leybold-Heraeus company, Hanau (Figure 4). Its principal elements are shown schematically in Figure 5. The material to be pressed was heated by open radiating heating elements. Graphite discs were placed between the press plates and the samples. In their ground state they guarantee satisfactory surface quality for the samples. No additional release agent was necessary to prevent welding of the plate to the material pressed.

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Figure 4. Vacuum diffusion welding chamber (Leybold-Heraeus)

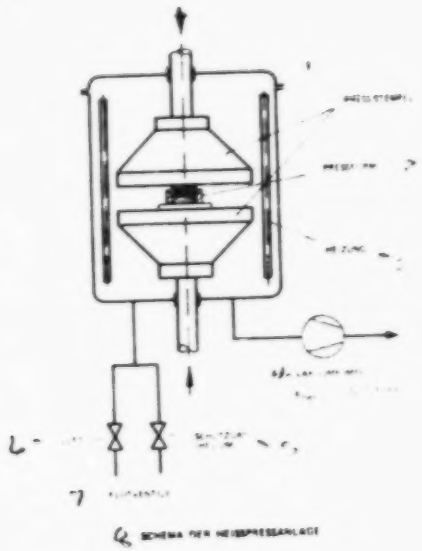

Figure 5. Schematic structure of the diffusion welding chamber.

1. Press plungers
2. Pressed shape
3. Heating
4. Vacuum pump
5. Protective gas (helium)
6. Air
7. Flood valves
8. Schematic of the hot press system

The welding was done under the following conditions:

Welding temperature	560°C
Welding time	1 hour
Applied pressure	3.5 kp/mm²

An AlMgSi alloy was used as the matrix and film.

The starting materials for the joining tests were:

1. Borsic aluminum plate, produced from single-layered tapes by the MBB company, with some 60% by volume of borsic fibers. *
2. Borsic aluminum plate, produced by diffusion welding. The starting material was tapes from the Hamilton Standard company and ribbons prepared at Dornier by plasma spraying. The fiber proportion of these plates was about 50% by volume.

Four-layered plates were welded as a rule. Their structure can be seen from the schematic drawing in Figure 6. The boron fibers, fixed by the plasma-sprayed aluminum layer, lie on the sheets of AlMgSi alloy. In order to improve the surface quality, other sheets were placed around the plate package.

Three different types of bonding were investigated:

1. singly overlapped bonds
2. doubly overlapped bonds
3. stacked bonds in the sense of a stepped overlapping free of bending moments

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* Translator's note: Borsic is not defined in this work; but the name suggests boron/silicon carbide.

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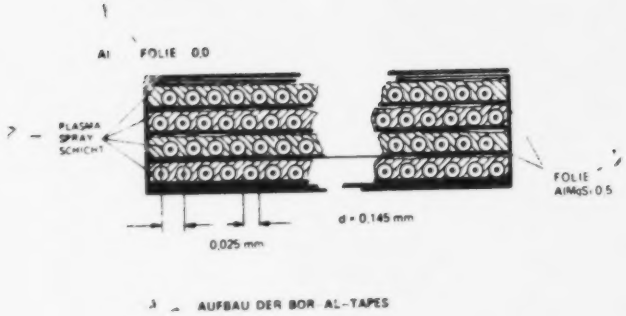

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Figure 6. Section through Borsic-aluminum plate (schematic)

1. sheet
2. plasma-sprayed layer
3. sheet
4. Structure of the Bor-Al tapes

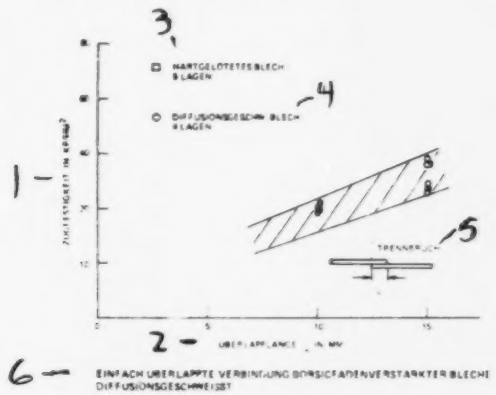

Figure 7. Tensile strength of singly overlapped Borsic-Al plates as a function of the overlap length.

1. Tensile strength, kp/mm²
2. Overlap length, $l_ü$ in mm
3. Hard-soldered plate, 5 layers
4. Diffusion welded plate, 4 layers
5. Separation fracture
6. Singly overlapped bond of diffusion-welded Borsic-fiber-reinforced plates.

The results of the static tensile tests of the singly overlapped bond are plotted in Figure 7. Overlap lengths of 10 and 15 mm were tested. In the static test, there was a smooth fracture at the transition between the overlap and the plate.

It appears from this that the four-layer diffusion-welded plate will stand loads that compare with those for the five-layer hard-soldered plate. The reason is the lower strength of the individual fibers in the hard-soldered boron-aluminum plate compared with the fibers in the diffusion-welded plates. The breaking strength of the fibers was determined after they were separated from the matrix by means of sodium hydroxide. The increase in strength with increasing overlap length, observed in Figure 7, is considered a result of the reduction in stress increase which that causes.

For the doubly overlapped samples (Figure 8), overlap lengths of 5, 10 and 15 mm were investigated. Here, too, the fracture in the static tensile test was always a smooth break at the step in the plates rather than in the bonded surface. Only at the minimum overlap length of 5 mm did occasional mixes of separation and shear fracture appear. In this case, also, accordingly, the local stress increase is primarily responsible, and not the shear strength of the bond. The stress increase diminishes as the overlap length increases. In comparison with singly overlapped bonds, the strength obtained was about twice as great, on the average.

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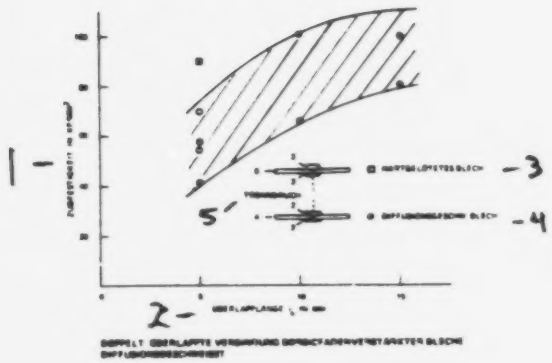

Figure 8. Tensile strength of doubly overlapped Borsic-Al plate as a function of the overlap length.

1. Tensile strength in kp/mm²
2. Overlap length, $l_ü$, in mm
3. Hard-soldered plate
4. Diffusion-welded plate
5. Separation fracture

The so-called stacked or stepped bond is certainly more favorable from the viewpoint of weight than the doubly overlapped bond, but it is not at strong as the doubly overlapped bond, at least not with overlap lengths of 10 and 15 mm (Figure 9).

Within the range of variation investigated, between 5 and /371
15 mm, no clear dependence on the overlap length is detectable. To be sure, the maximum strength of the bond has already been reached at 5 mm overlap. For this bond type also, there was only a smooth separation fracture in the static tensile test, starting at the step in the joint of the outer tapes. The stress increase, because of

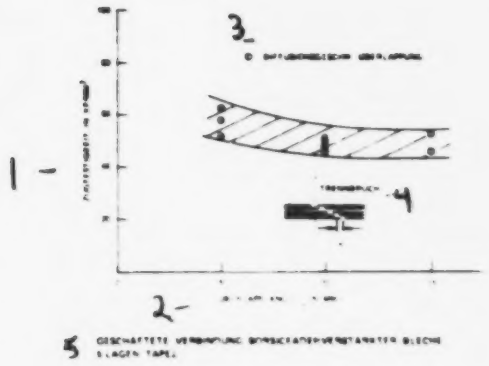

Figure 9. Tensile strength of a stacked bond between Borsic-Al plates as a function of the overlap length.

1. Tensile strength in kp/mm²
2. Overlap length, $l_ü$, in mm
3. Diffusion-welded overlap
4. Separation fracture
5. Stacked bonding of borsic-fiber-reinforced plates of 5-layer tapes

the low step height, is apparently no longer influenced by the overlap length. The fracture occurs because of the edge step just as for a corresponding plate in which the outer fiber layer was separated.

The strength ranking from the static tensile tests is confirmed for the three bonding forms mentioned in the alternating-load behavior (Figure 10). That is, the doubly overlapped sample has higher lifetime than the stacked or the singly overlapped bond. It should be noted that the doubly overlapped sample had an overlap length of 5 mm,

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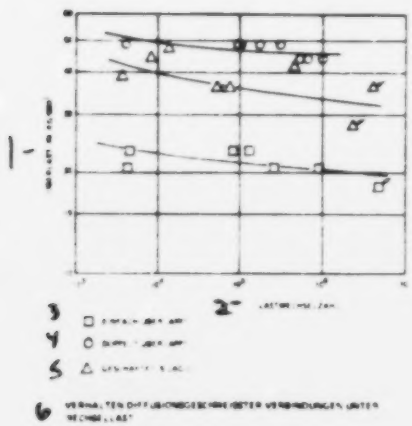

Figure 10. Alternating load behavior of diffusion-welded bonds in the tensile threshold test (R = 0.1).

1. Overload in kg/mm²
2. Load cycles
3. Singly overlapped
4. Doubly overlapped
5. Stacked, 5-layer
6. Behavior of diffusion-welded bonds under alternating load

while the singly overlapped sample had an overlap length of 10 mm. As a result, the bonding area of the singly and doubly overlapped samples is equal.

In contrat to the static tensile test, there was also shear fracture in many cases of dynamic loading; that is, the bond itself failed.

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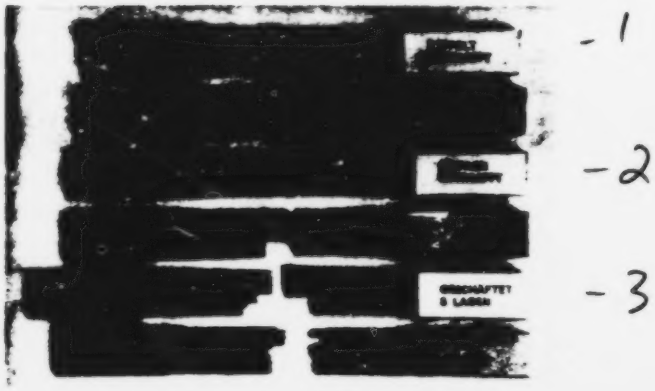

Figure 11. Fracture forms of dynamically stressed diffusion-welded bonds.

1. Doubly overlapped
2. Singly overlapped
3. Stacked - 5 layers

Figure 11 shows the typical fracture pictures for the three different bonding forms. The upper one of the two fracture forms shown represents the usual case. For the doubly overlapped sample, the smooth separation fracture appeared most often. Only occasionally does one find separation of the bond. The singly overlapped bond, however, fails predominantly in the joint area itself. The bending moment produced by the displacement of the plates by the plate thickness acts in the manner of a tensile stress on the joint surface. The stacked samples also always fail in the bond. From the scanning electron micrograph (Figure 12), /373 one can recognize the typical band structure of a fatigue break characterizing the progress of the crack along the boron fibers. The fracture area in Figure 13 shows a bond

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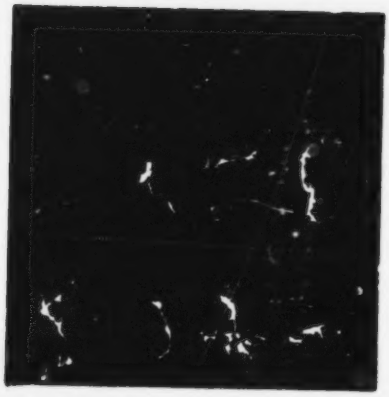

Figure 12. Interlaminar fatigue fracture, 200x

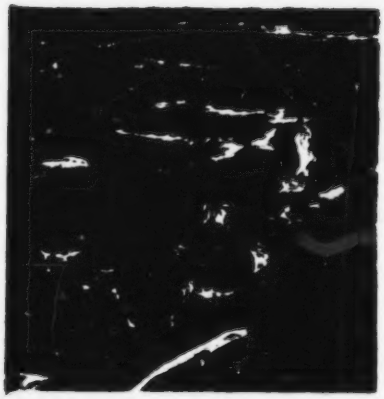

Figure 13. Fracture surface at the plate step with separation between cover and core plate, 100x

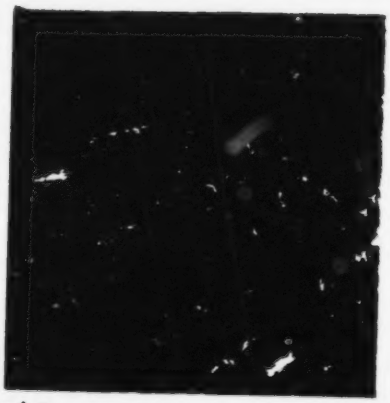

Figure 14. Fracture surface at the plate step with satisfactory bonding between cover and core plate, 50x

failure between the cover plate and the core plate. In contrast, the scanning electron micrograph, also made from the plate step, shows satisfactory bonding between the outer plate and the core plate.

In summary, it may be said that the bond strength achieved with diffusion welding is completely sufficient to transfer forces with four-layer plates 0.7 to 0.8 mm thick with static loading in the tensile test. Overlap lengths of 5 mm already suffice. This corresponds to a ratio for d/l, of 1:7. Lower overlap lengths than 5 mm are not worth trying for because of production technology reasons.

It is not the shear stress which causes failure in diffusion-welded joints, but the local stress concentrations at the steps of the bonding plates, and the bending moments for single-layer bonds. For the step-like stacked bond the edge notch severely reduces the strength.

Measures leading to lower step stress and therefore to higher loadability of the bonds include the following, for instance:

- increasing the overlap length
- bond shape free of bending moment
- suitable shaping of the overlapping plates for smooth force transfer
- smallest possible step height for the overlapping plates

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The results of the alternating load tests show a somewhat different picture than the static tensile test:

Some of the samples stressed at the tensile threshold test exhibit shear fractures. For the singly overlapped bonds this is immediately understandable because of the bending moments that occur, which cause a tensile stress perpendicular to the joint surface. For the doubly overlapped bond, which is free of bending moments, on the other hand, the breaks occur without exception at the plate step in the center of the bonding plates. The stepwise stacked sample, on the other hand, exhibits predominantly shear breakage, even with overlap lengths of 15 mm. We cannot at this time give a reasonable explanation for this behavior.

Comparison with hard-soldered bonds, which were investigated by Kreider, shows that almost identical fracture modes appear in the static tensile test. Of course, Kreider kept the overlap length constant at 9 mm in his tests. If one wishes to weigh the advantages and disadvantages of diffusion welding versus hard soldering, then from the viewpoint of production technology, there is a strong advantage for hard soldering. The advantages of diffusion welding are derived more from the metallurgical view. They are:

- the Borsic fibers are not damaged
- there is no use of solder with the possible consequences of galvanic corrosion
- higher hot strength of the bond.

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